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Control of thermal barrier performance by optimized nanoparticle size and experimental evaluation using a solar simulator

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ABSTRACT

An experimental investigation to evaluate the radiative properties of a selectively transparent thin coating on a substrate of a different material has been performed in order to evaluate its thermal behavior for applications where a low temperature at the surface exposed to the sun is desired. Copper (II) oxide (CuO) micro-particles have been used to create a pigmented coating on a paper substrate. The particle volume fraction and size have been optimized by the theoretical methodology. The spectral reflectance was measured using spectroscopy in the visible (VIS) and near-infrared (NIR) regions. The spectral emissivity was evaluated from the reflectance in IR region. The temperatures of the designed coatings and typical black paints are measured in a solar simulator. The temperature measurement was simulated by numerical analysis. The temperature of CuO coating on standard white paper was 10 °C lower than the ones of typical black paint while keeping the desired dark tone.

1. Introduction

Products such as cars and buildings are usually exposed to a great deal of sunlight. In many cases, dark-color coatings are preferably used on these products for reasons of appearance. However, these dark coatings absorb a large amount of solar irradiation in the visible (VIS) and near-infrared (NIR) regions. Therefore, the interior temperature becomes high and creates a large cooling load for air conditioning systems. The resultant energy consumption contributes to environmental problems such as the greenhouse effect and urban heat islands.

For the situation where a surface is to be kept cool while being exposed to sunlight, the surface should have maximum reflectance of solar energy. Such a coating is often called “cool coating”. The use of cool pigmented coating on exteriors has been proposed as a countermeasure of these problems [1–3]. Johnson et al. [1] optimized the zinc oxide pigment in a thermal control coating used for spacecraft walls in order to attain maximum diffuse solar reflectance at a low film thickness, and at low pigment concentrations. Sreeram et al. [2] explored colored pigments with high near-infrared reflectance and not based on toxic metal ions. Two doping pigments, Ce–Pr–Mo and Ce–Pr–Fe, have been developed to produce reddish brown and reddish orange colors, respectively. Moreover, Synnefa et al. [3] studied the effect of 14 types of reflective coatings which are commercially available on

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the lowering of surface temperatures of buildings and other surfaces of urban environments, and thus tested their ability to lower ambient temperatures and fight the heat island effect. Several studies have investigated “cool coatings”. However, the effects of particle size on spectral behavior have not been investigated, especially with respect to black coating.

With regard to the control of the radiative properties on the surface, several studies also have been done in the area of nanotechnology. A *morpho* butterfly controls light by nano structures of scale powder, and this leads to the blue appearance of their wings [4]. Maruyama et al. [5] utilized nanotechnology to control the radiative properties of solid surfaces by controlling surface structures using a two-dimensional array of microcavities. Here, it was shown that the thermal radiation is precisely controllable by changing the size of the microcavity. Greffet et al. [6] studied the directionality control of radiation by grating of the surface. It is well known that properties of thermal radiation change according to the surface structure. However, these technologies are not suitable for coating the exteriors of cars, homes and buildings.

In our research group, a cool pigmented coating using controlled size submicron particles has been proposed [7]. The solar energy that reaches Earth's surface in the wavelength range from 0.3 to 2.5 μm is divided into three parts: the ultraviolet (UV) region (5%), VIS region (43%), and NIR region (52%) [8]. Our desired coating reflects NIR radiation and transmits long infrared (IR) rays emitted from the substrate, while it decreases the reflectance of VIS light. Fig. 1 shows a schematic of the desired coating used as a thermal barrier coating. Such a pigmented coating that controls radiation has been studied in our research group. Maruyama et al. [9] established a method of making a database of the radiative properties of single particles. Baneshi et al. [7] proposed a theoretical design method for optimizing the pigmented coatings both thermally and aesthetically, by controlling the size and volume fraction of particles and coating thickness. They used the radiation element method by ray emission model (REM^2) for optimization of the reflective performance [10]. REM^2 is a generalized numerical method for analyzing radiation transfer in non-gray and anisotropic participating media with specular and/or diffuse surfaces. In their paper [10], titanium dioxide, a common white pigment, is used as the pigment. Baneshi et al. [11] also used the theoretical design method to study copper oxide (CuO)-pigmented coating, which is both dark and cool. Using their method, a black-color coating pigmented with CuO submicron particles with high reflectance in the NIR region was achieved [12]. Baneshi et al. [13] also conducted a radiation thermal analysis to evaluate the thermal barrier performance of the pigmented coatings. Nevertheless, the thermal response of the cool coating was not investigated. Additionally, the emissivity of the coating was not estimated.

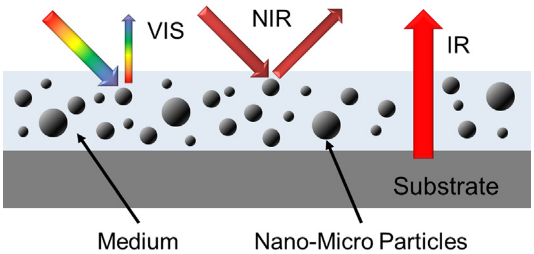

Fig. 1. Schematic of a cool pigmented coating.

As mentioned above, a black-color coating pigmented with high NIR reflectance using CuO particles with optimum size has previously been modeled theoretically [11] and achieved experimentally [12]. In this paper, the objective was to investigate the thermal response of spectral-selective coatings pigmented with CuO particles, experimentally. The coating was optimized theoretically as explained in Ref. [11] and prepared. Here, the spectral reflectance of the coating was measured. Additionally, the emissivity was also estimated. For the performance of the thermal barrier, the emissivity is important as shown in Fig. 1. Finally, the temperatures of the samples were measured inside the solar simulator to evaluate their thermal response. The effects of particle size, volume fraction and coating thickness on thermal and esthetic behaviors are discussed. Additionally, thermal analysis was conducted to validate the temperature measurement.

2. Experimental setup and procedures

2.1. Coating preparation

2.1.1. Definition of optimization parameter

In previous studies [7,11,14,15], the optimization parameter was defined to find the suitable pigment particle. The performance parameter of pigmented coating for solar reflectance in the solar spectrum region is proposed as [12]

$$\rho_{TSR} = \frac{\int_{0.30}^{2.50} \rho(\lambda) I(\lambda) d\lambda}{\int_{0.30}^{2.50} I(\lambda) d\lambda}, \tag{1}$$

where $I(\lambda)$ is the solar irradiation and $\rho(\lambda)$ is the spectral reflectance of the pigmented coating. A parameter that evaluates the aesthetic performance of a pigmented coating by considering spectral eye sensitivity is defined as follows:

$$\rho_{VIS} = \frac{\int_{0.38}^{0.78} \rho(\lambda) \eta(\lambda) I(\lambda) d\lambda}{\int_{0.38}^{0.78} I(\lambda) d\lambda}, \tag{2}$$

where $\eta(\lambda)$ is the normalized standard luminous efficiency. The optimization parameter R can be calculated as follows [12]:

$$R = \frac{\rho_{TSR}}{\rho_{VIS}}. \tag{3}$$

In order to achieve an optimized coating, the parameter R should be maximized.

2.1.2. Preparation method

For the experiment, pigmented coatings were made using clear acrylic synthetic resin as the matrix, and standard black or white paper as a substrate. As the dispersed particles for black pigments, CuO powders were used. To investigate the effect of particle size on reflectivity and temperature, three powders with different nominal